Direct Search for Millicharged Particles with Correlated Quantum Sensors

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University of Science and Technology of China

宇宙背景中微子与暗物质探测研讨会

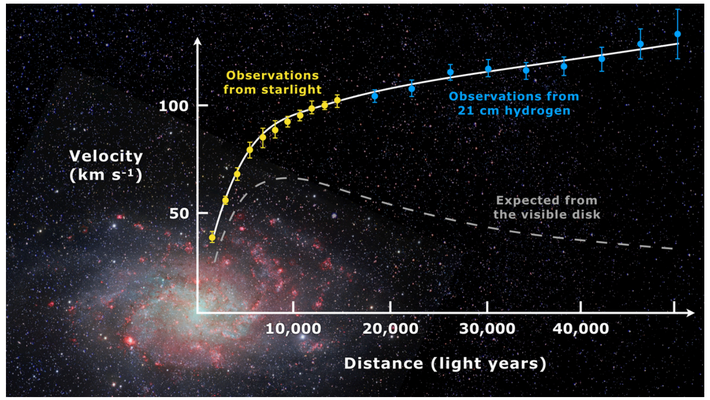
中国高等科学技术中心, 北京

October 30, 2026

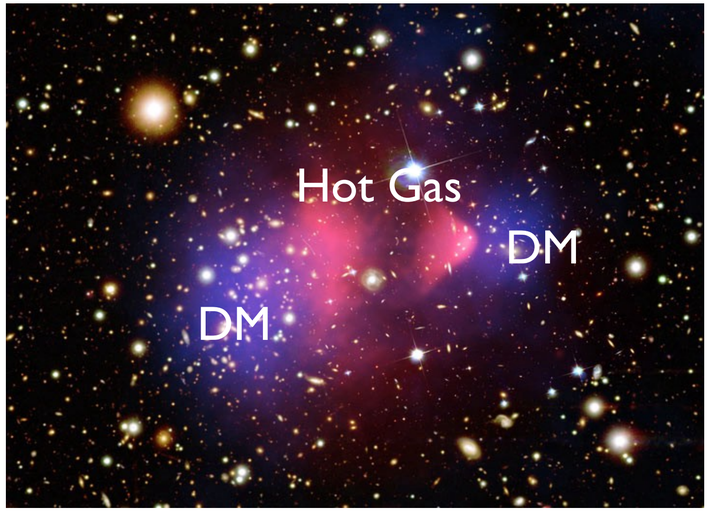
In collabration with: Haowen Su, Shiju Hu, Min Jiang, Xinhua Peng (experimentalists)
Bin Xu (theorist)

Dark Matter

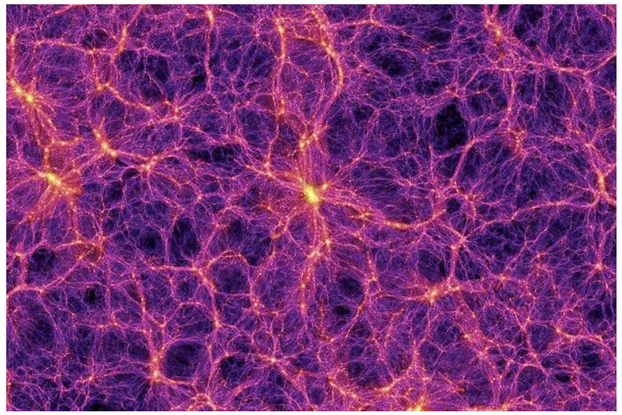
Numerous evidence for the existance of DM



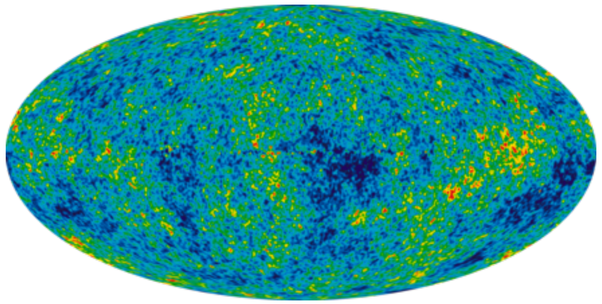
Galaxy (10^4-10^5 ly)



Galaxy Cluster (~10^6 ly)



Large Scale Structure (~10^7 ly)



Cosmic Microwave Background (~10^{10} ly)

What could Dark Matter be

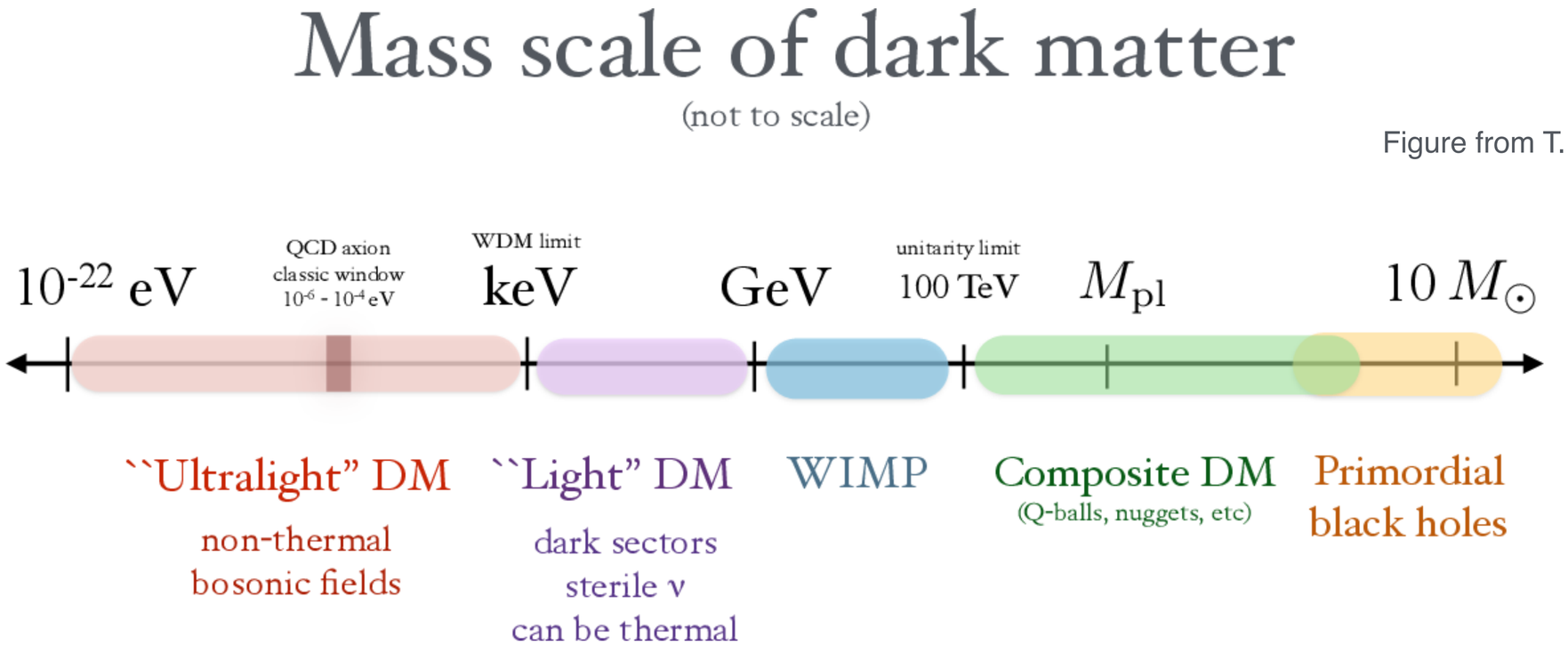


Figure from T. Lin (arXiv:1904.07915)

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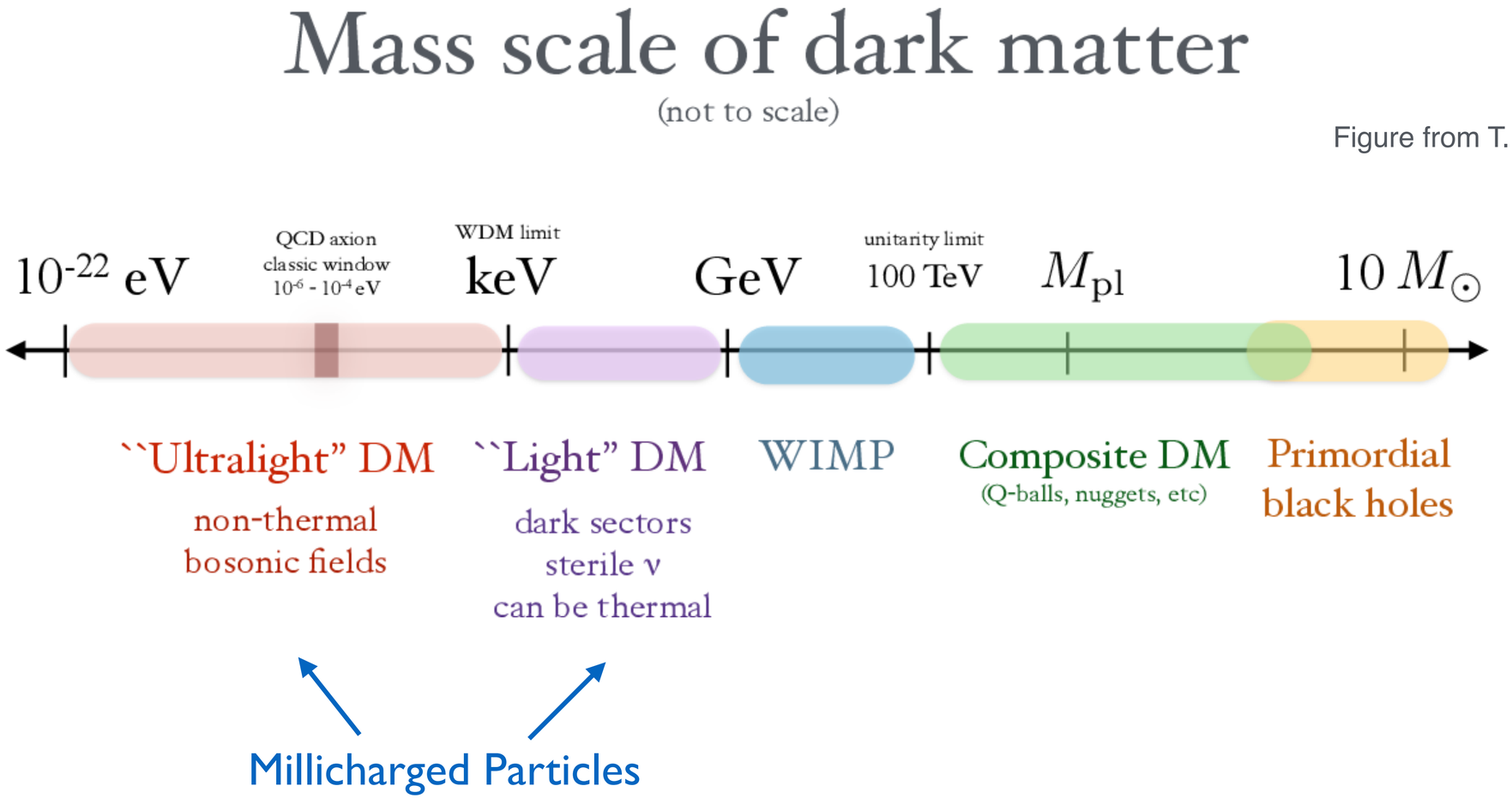

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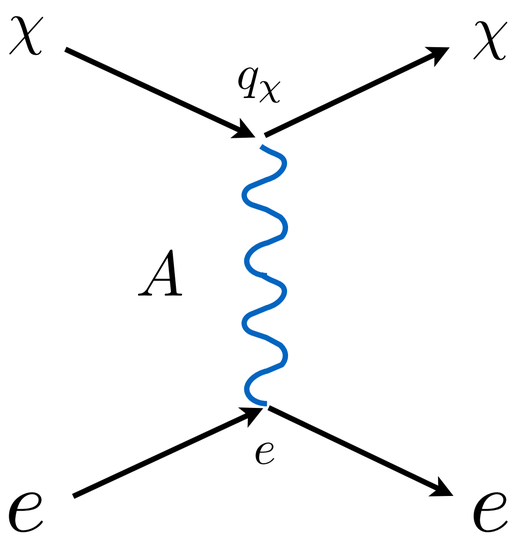
Millicharged Particles/Dark Matter

- MCP: particles with tiny electric charges

$$\mathcal{L}_\chi = \bar{\chi}(i\gamma^\mu \partial_\mu - m_\chi)\chi - q_\chi A_\mu \bar{\chi}\gamma^\mu \chi$$

$$q_\chi \ll e$$



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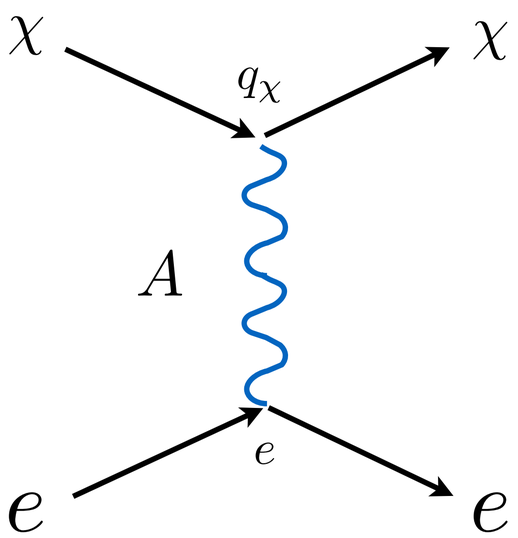
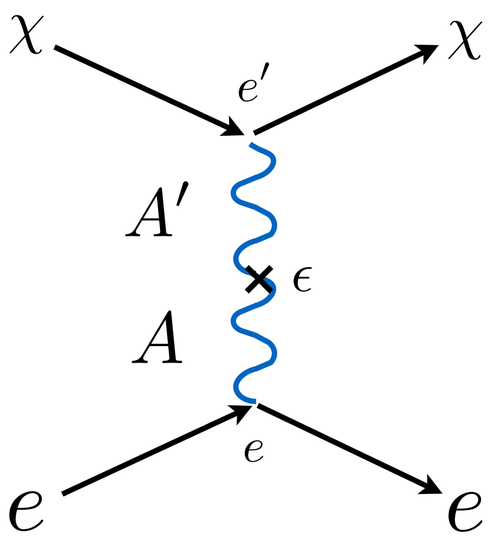
- Can be realized by introducing a dark photon mixing with the SM photon

$$q_\chi \sim \epsilon e'$$





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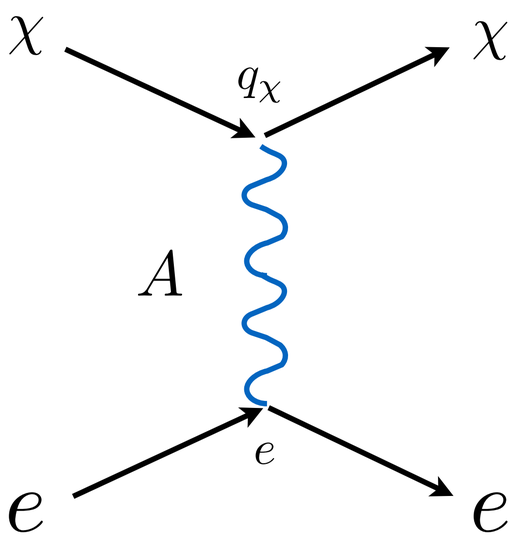

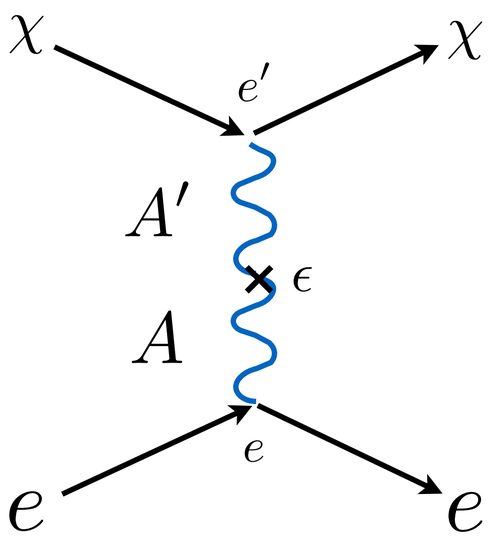

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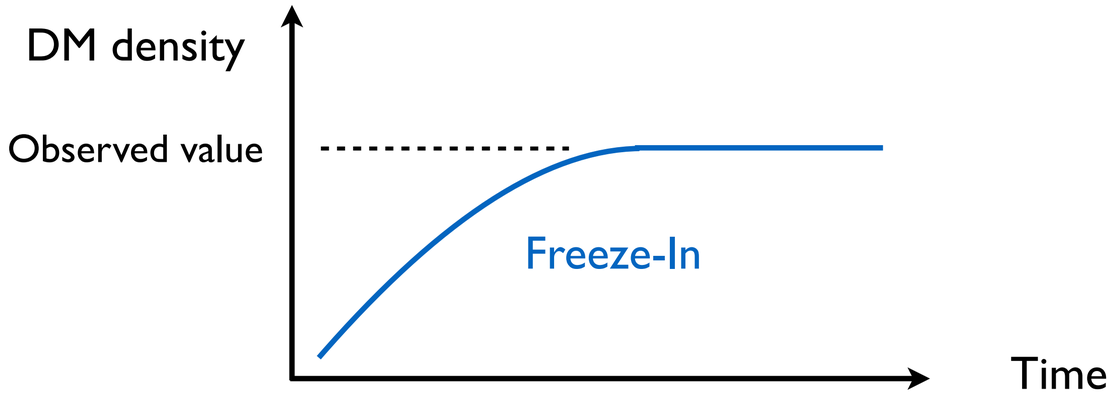
$$q_\chi \sim \epsilon e'$$

- DM Relic abundance

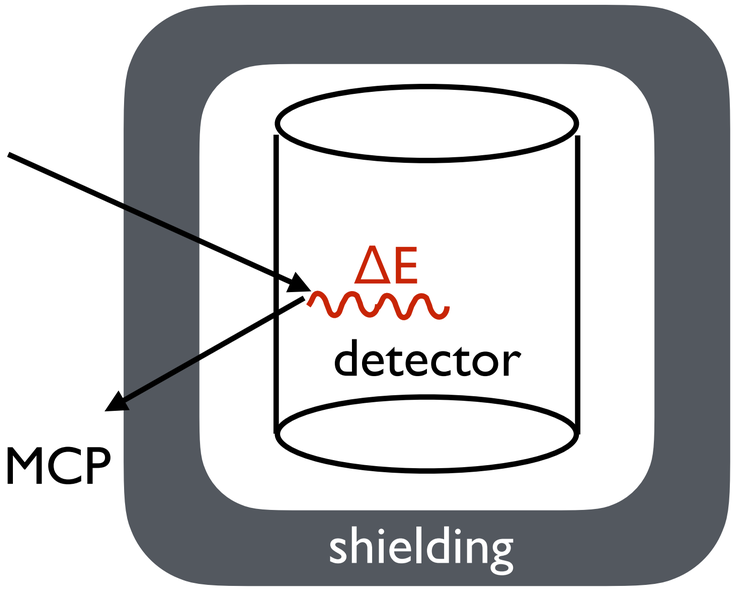
Freeze-in mechanism

Misalignment for light scalar MCP



Detecting MCP

Direct detection



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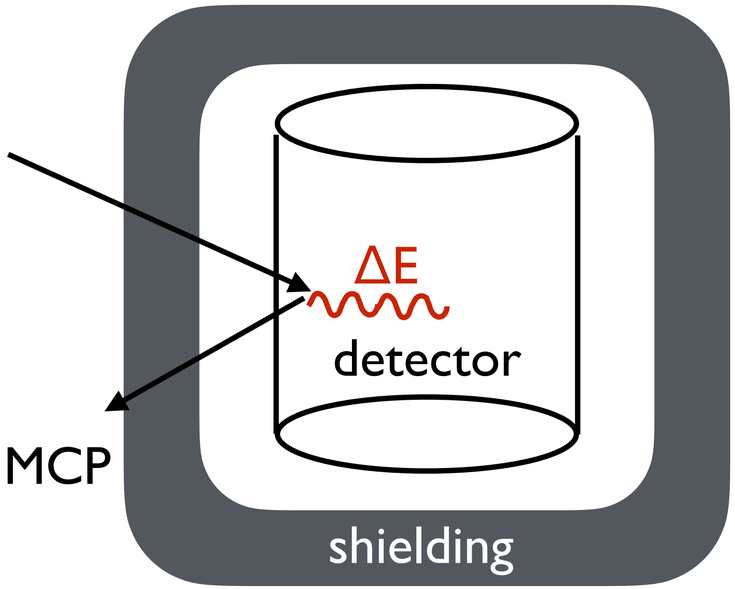
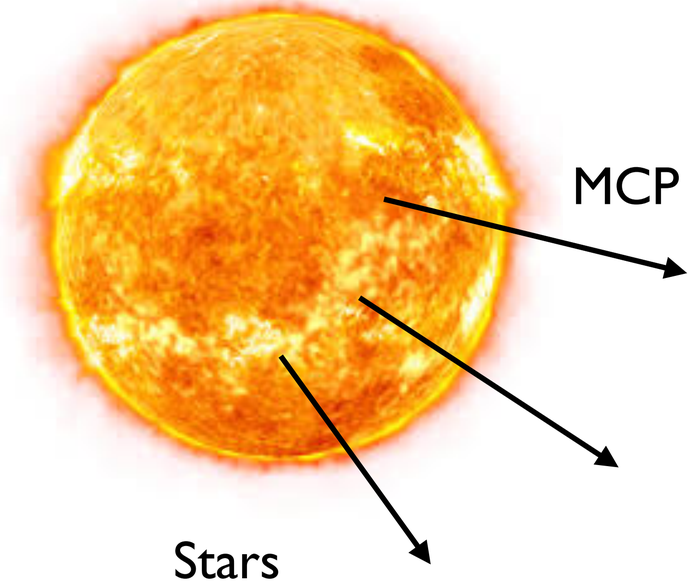


Astrophysics and cosmology



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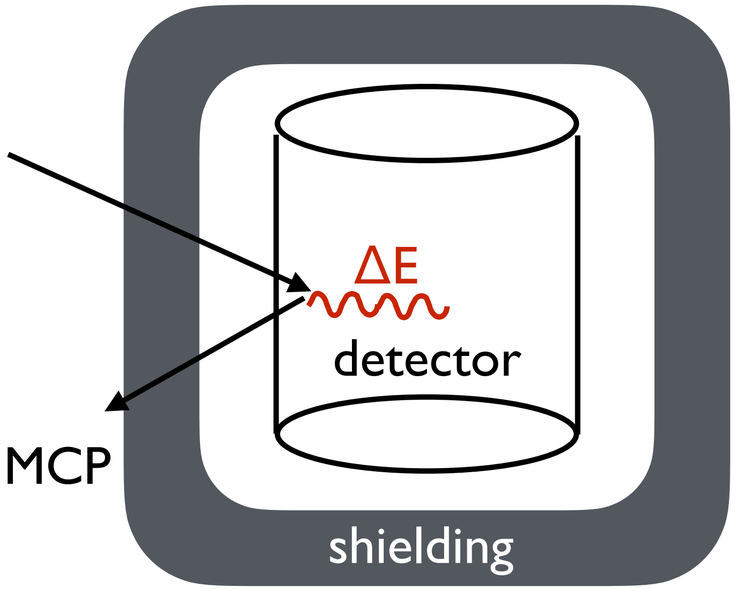

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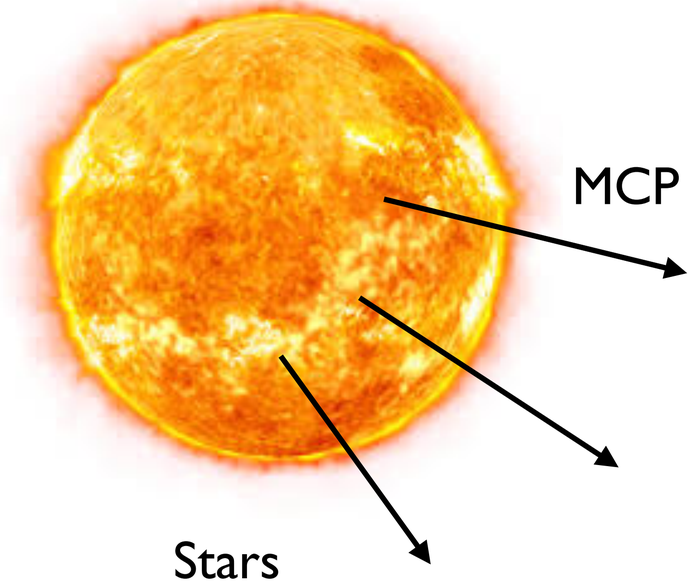
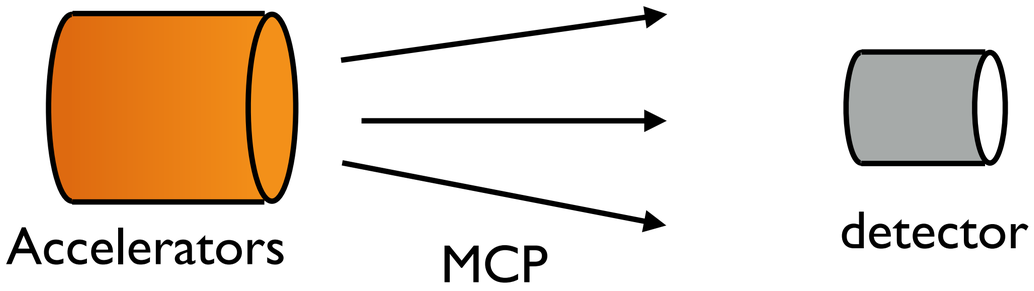
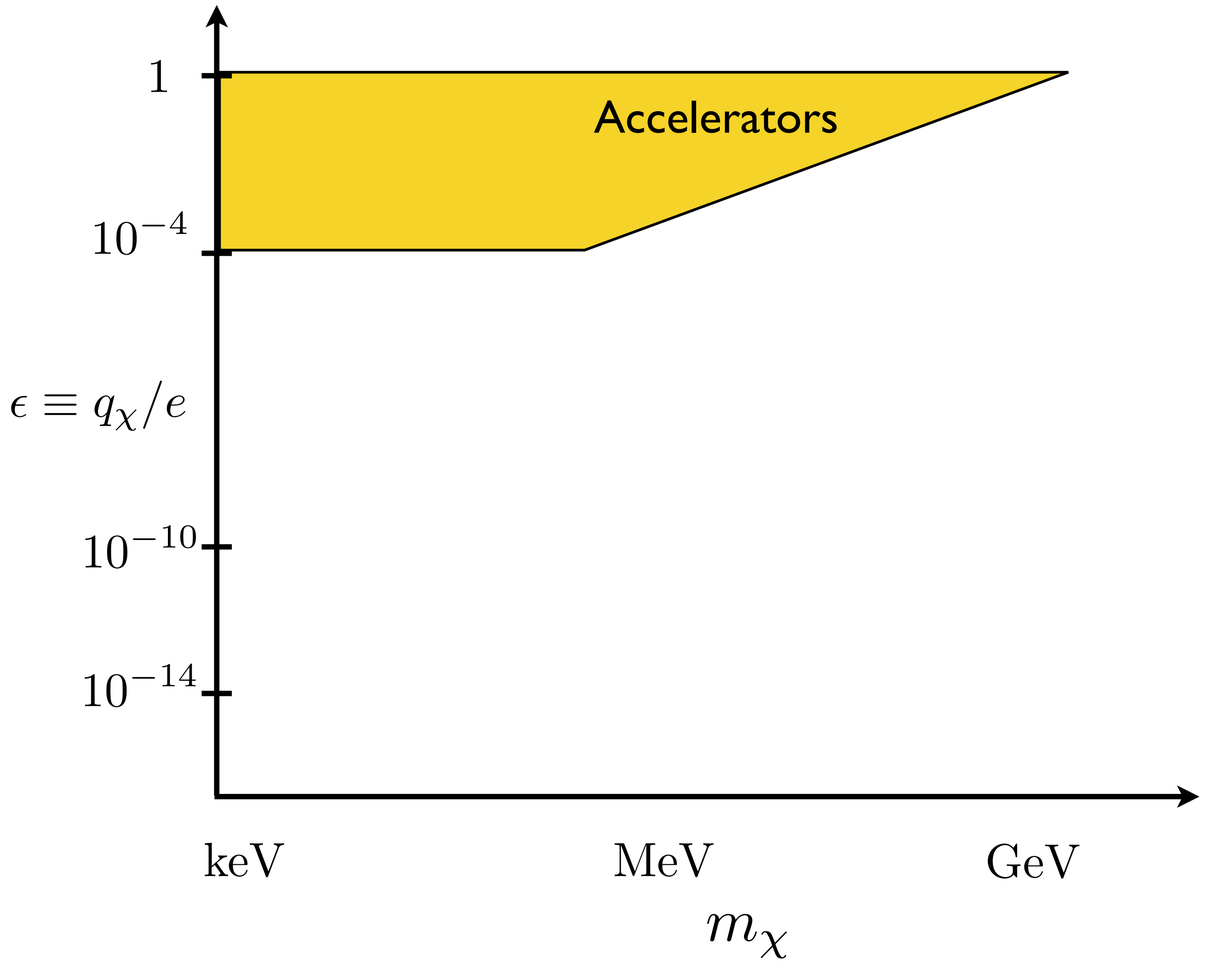


Accelerators/colliders



Constraints on MCP and millicharged DM

- Accelerators: MCP need not to be all DM



Constraints on MCP and millicharged DM

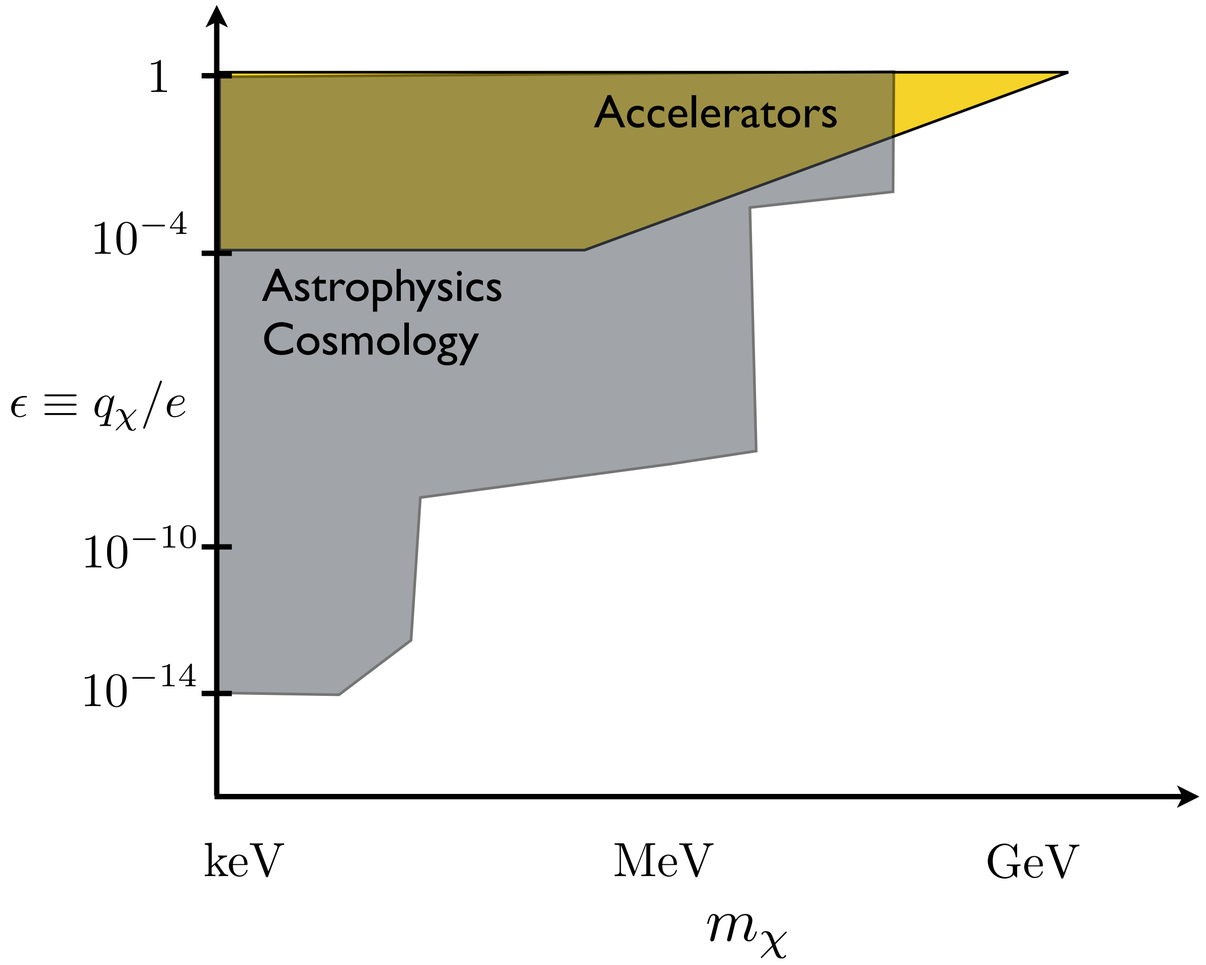
- Accelerators: MCP need not to be all DM
- Astrophyics and cosmology:

  Very strong: $\epsilon \lesssim 10^{-14}$ Stellar cooling

  Vogel, Redondo, *JCAP*, 2014

  but model dependent

  DeRocco,Graham, Rajendran, *PRD*, 2020



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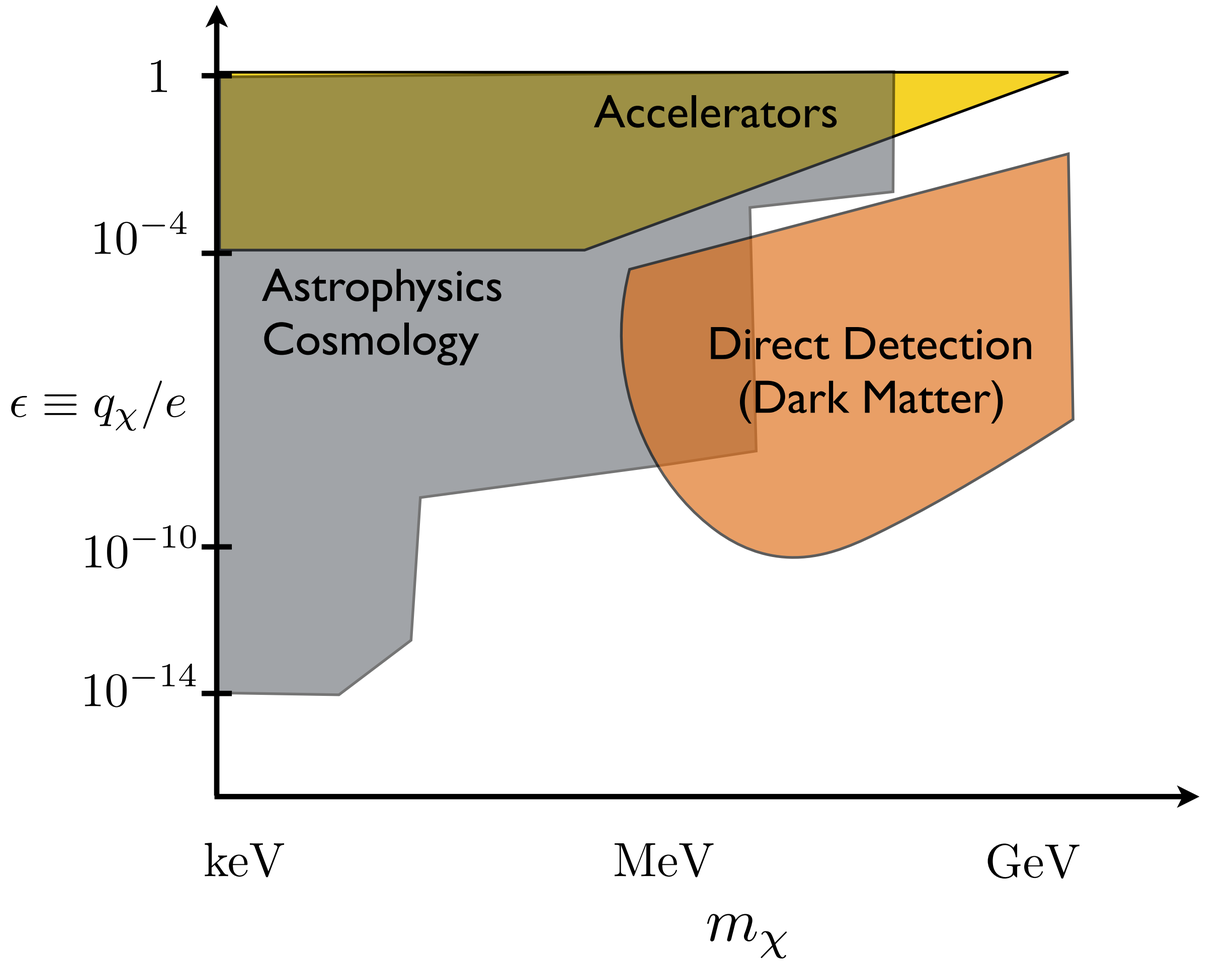
- Direct Detection: assuming all DM are MCP

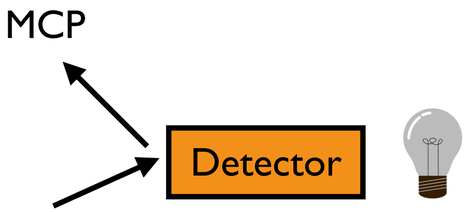
Low mass detection limited by detector threshold



How to detect low mass MCP?

Challenges

- Single particle interaction below the detector threshold



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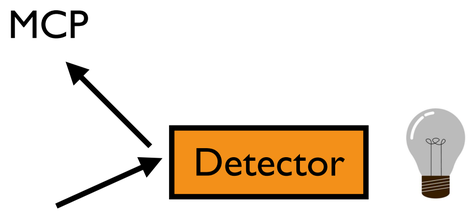
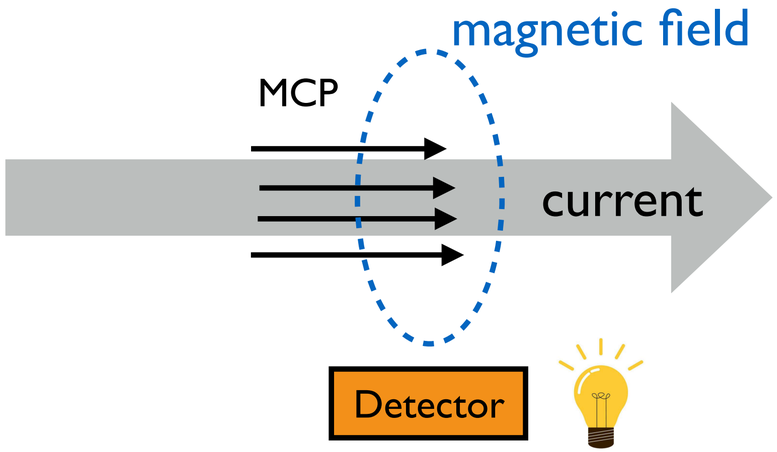


- Collection of particles can have visible signals



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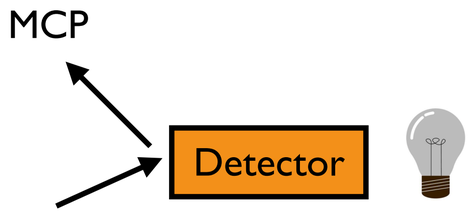

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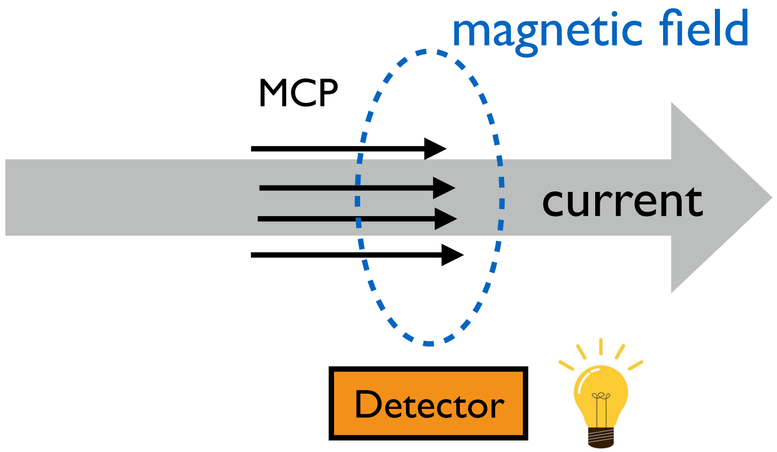
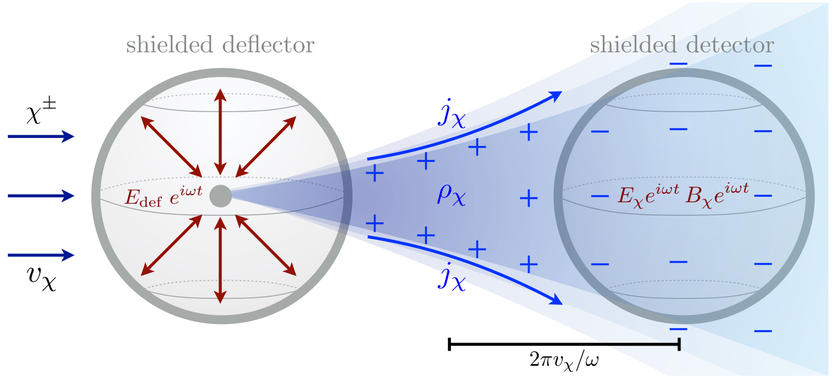


Proposals

- Direct Deflection

Berlin et.al, *PRL*, 2020



MCP are dark matter

How to detect low mass MCP?

Challenges

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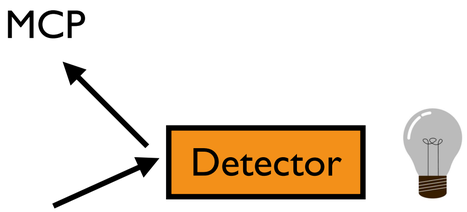

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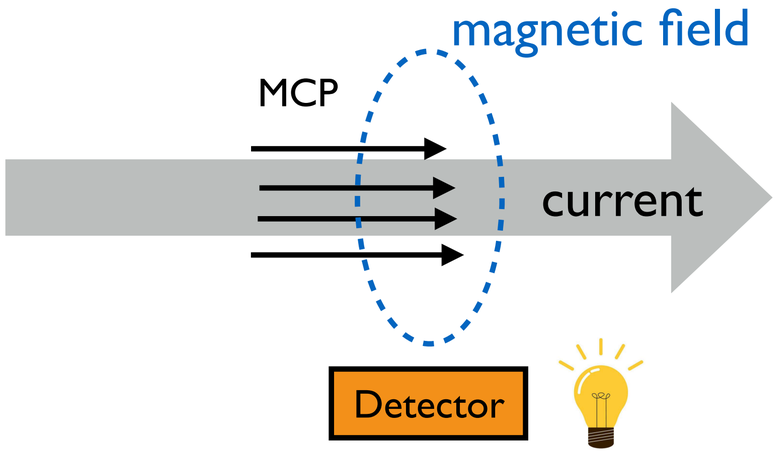

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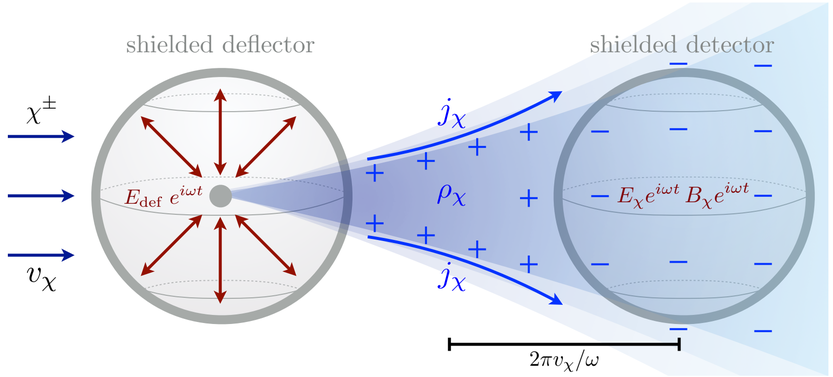
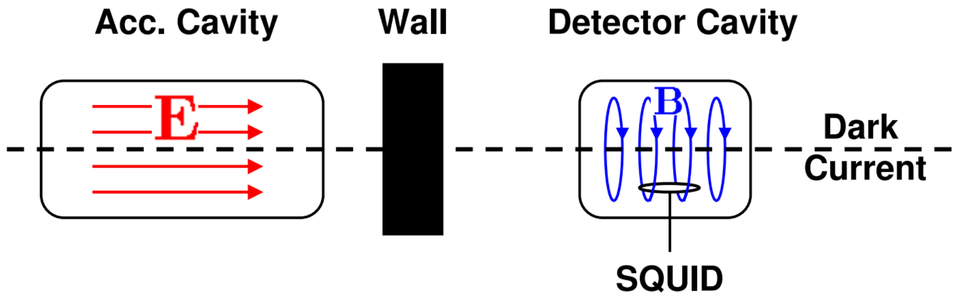


MCP are dark matter

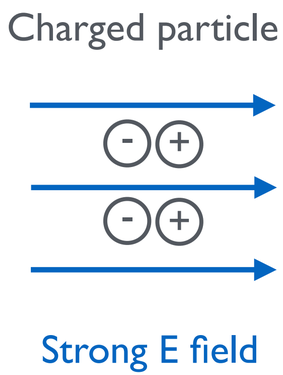
- Schwinger Production Gies, Jaeckel, Ringwald, *EPL*, 2006
  Berlin, Hook, *PRD*, 2020



light shining through a wall

Schwinger Production of MCP

- Strong electric fields can generate charged particle pair (non-perturbatively)



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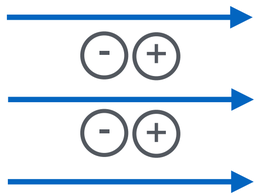
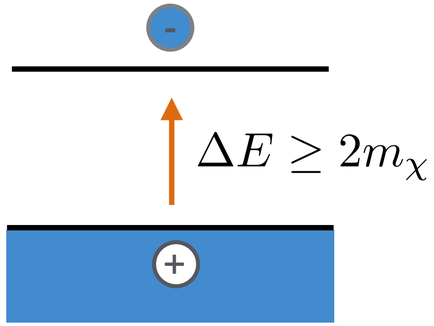
Charged particle pair



Strong E field



No E field

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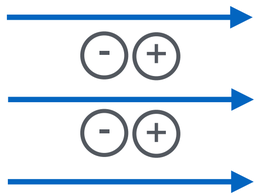
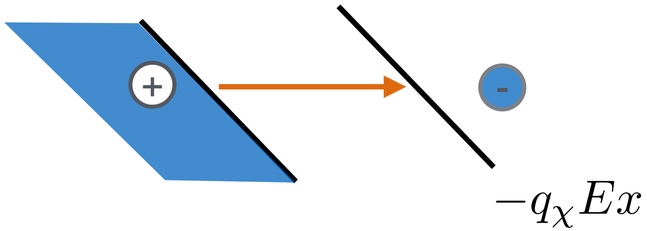
Charged particle pair



Strong E field

Tunneling



With E field

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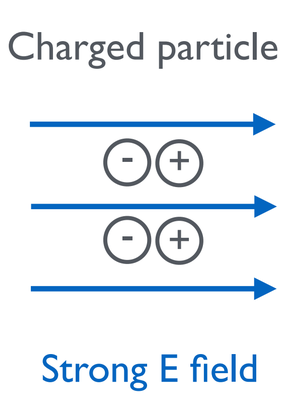

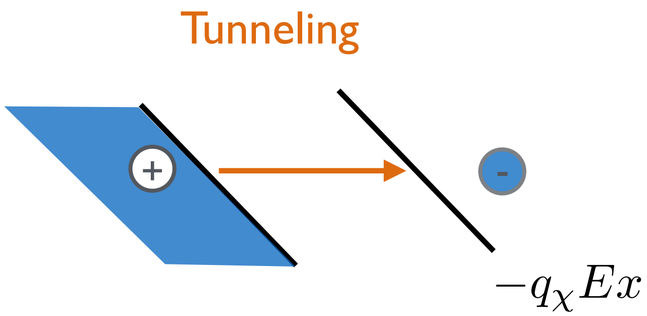

With E field

Production rate: $R = \frac{(q_\chi E)^2}{4\pi^3} \exp(-\pi E_{\rm cr}/E)$

Critical E field: $E_{\rm cr} \equiv m_\chi^2/q_\chi$

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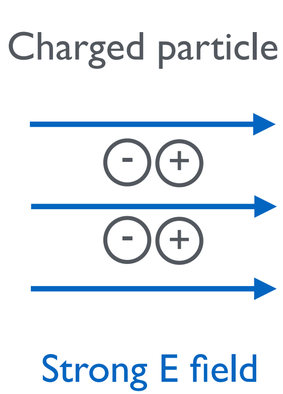

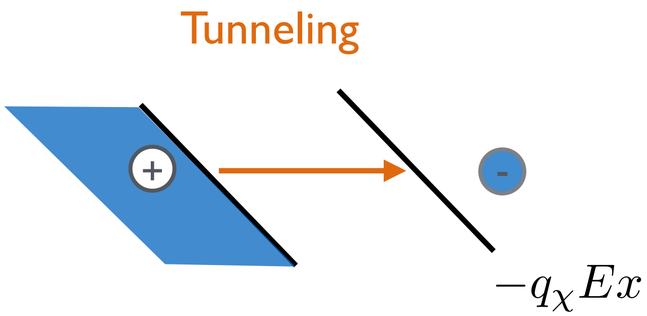

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Schwinger Production of MCP

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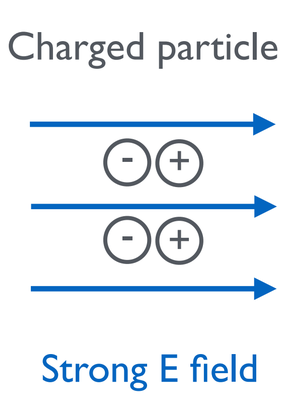

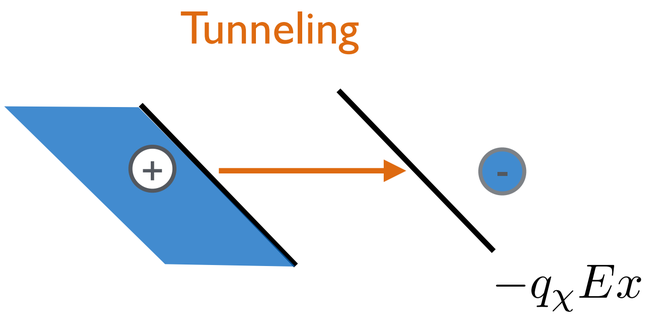

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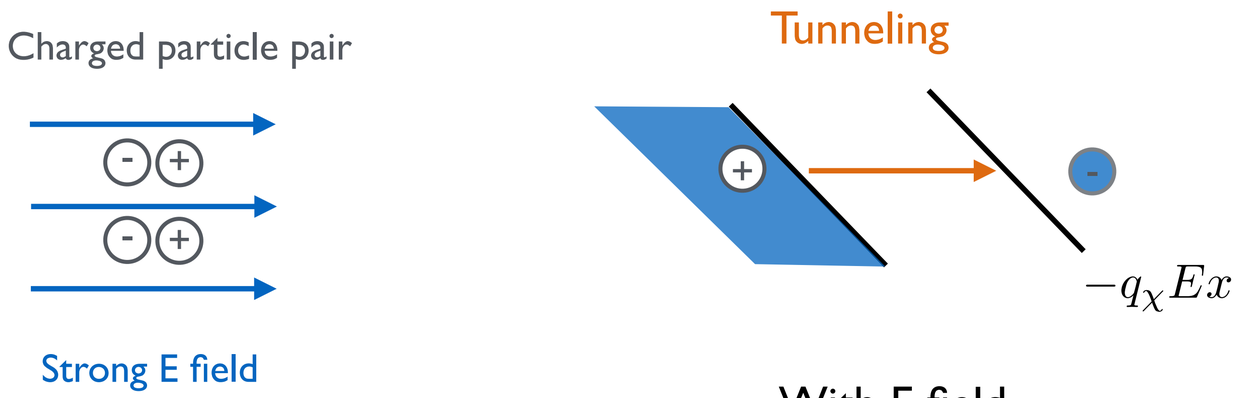

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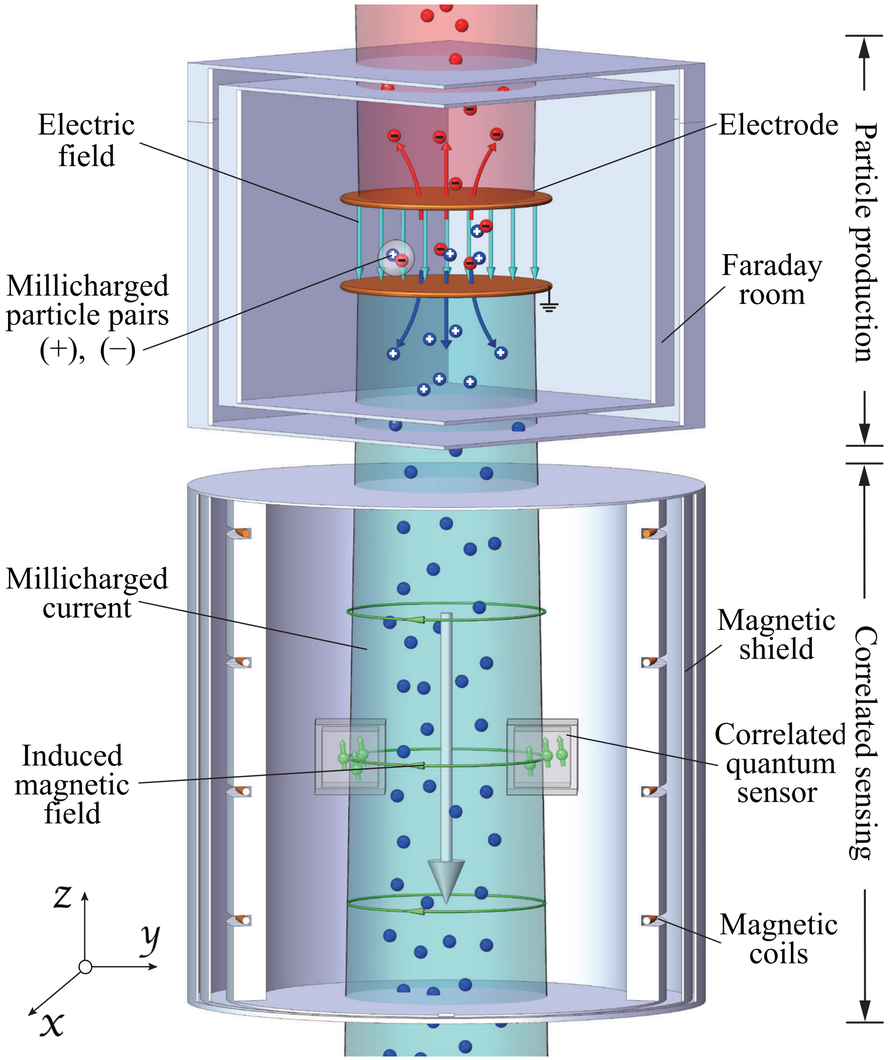
- Schwinger production of quasiparticles has been observed: semiconductors, graphene
- For light MCP, critical E can be accessible $E_{\rm cr} \sim 500\,{\rm kV/m} \left(\frac{m_\chi}{10^{-4}{\rm eV}}\right)^2 \left(\frac{10^{-7}}{\epsilon}\right)$

Our Experimental Search for MCP



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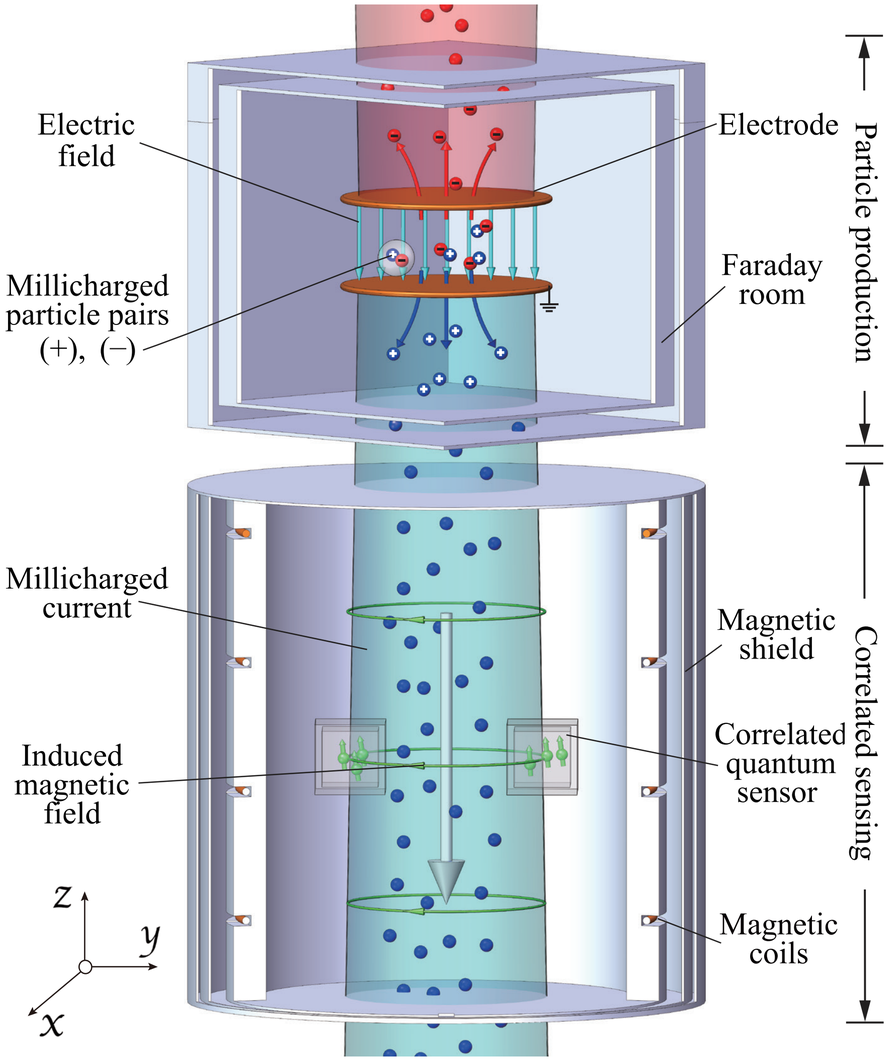

Production: Schwinger pair production

- Electric field generated by parallel-plate capacitor

  E≈24kV/cm below air electric breakdown

$$j_\chi \approx q_\chi \frac{(q_\chi E)^2}{4\pi^3} d \approx 10\,\mathrm{fA/cm^2} \left(\frac{\epsilon}{10^{-7}}\right)^3 \left(\frac{E}{10\,\mathrm{kV/cm}}\right)^2 \left(\frac{d}{1\,\mathrm{cm}}\right)$$

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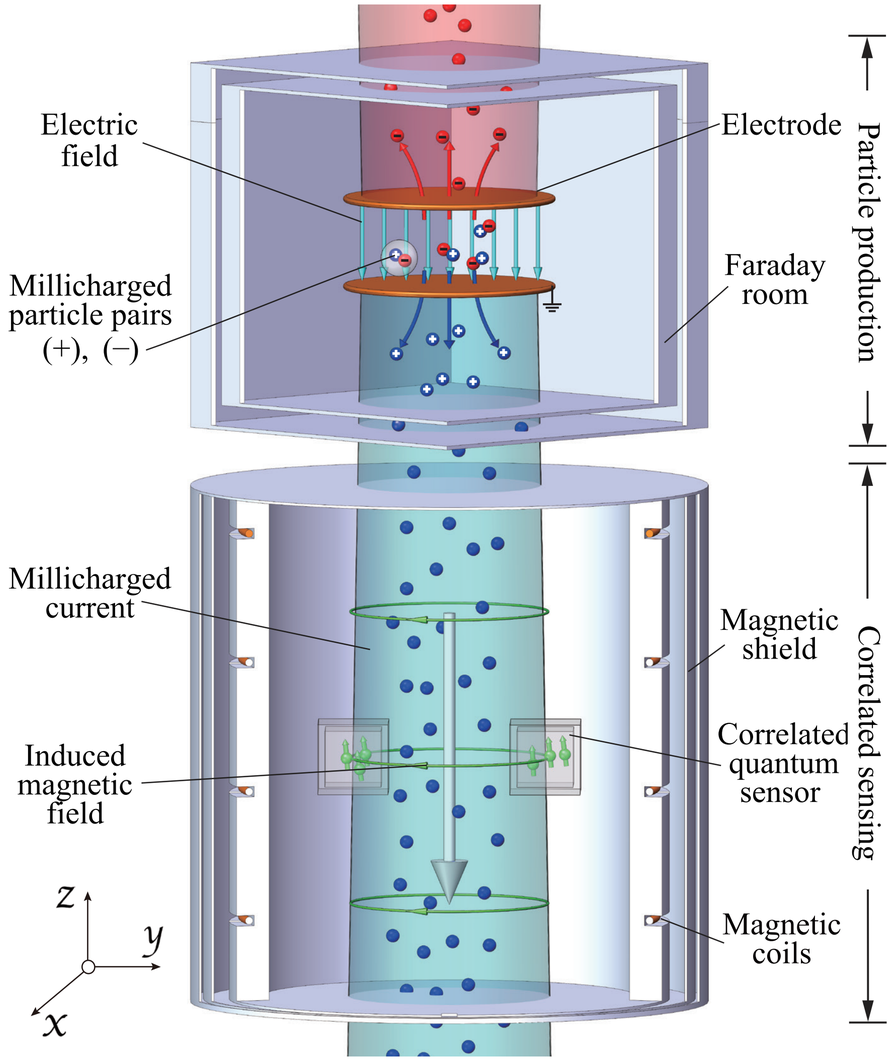

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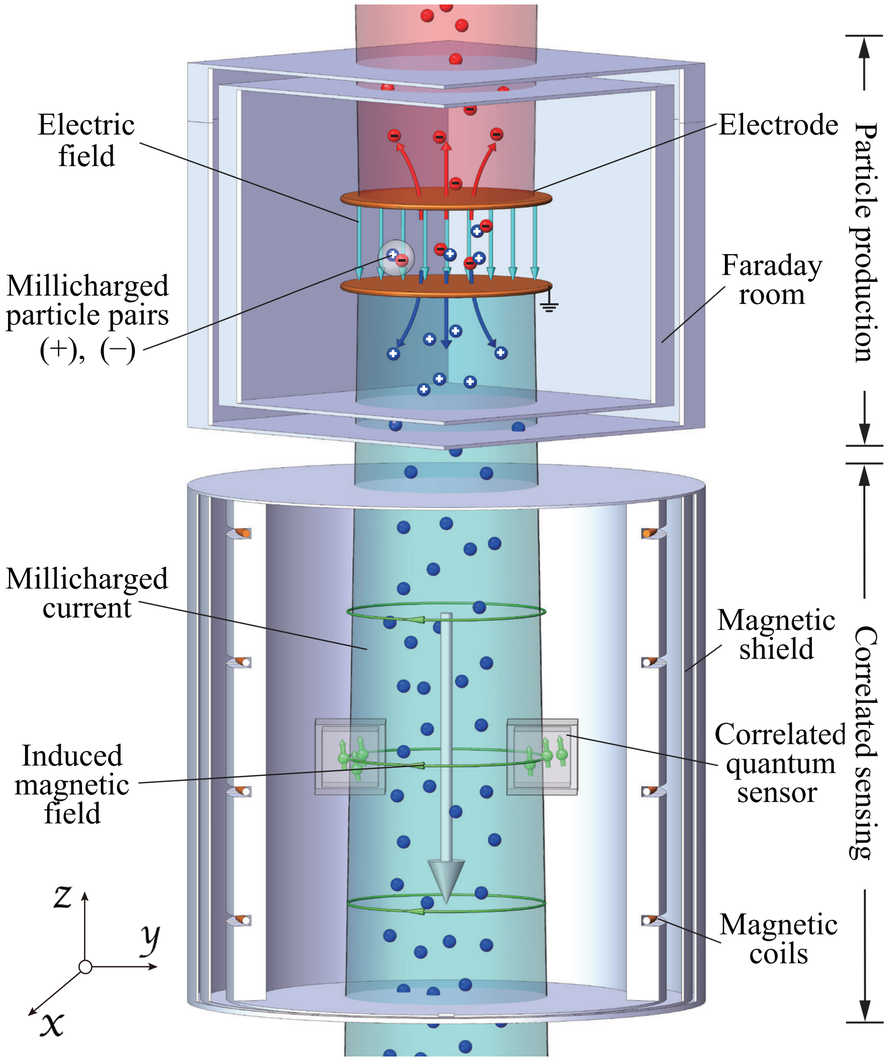
- Signal: induced magnetic field

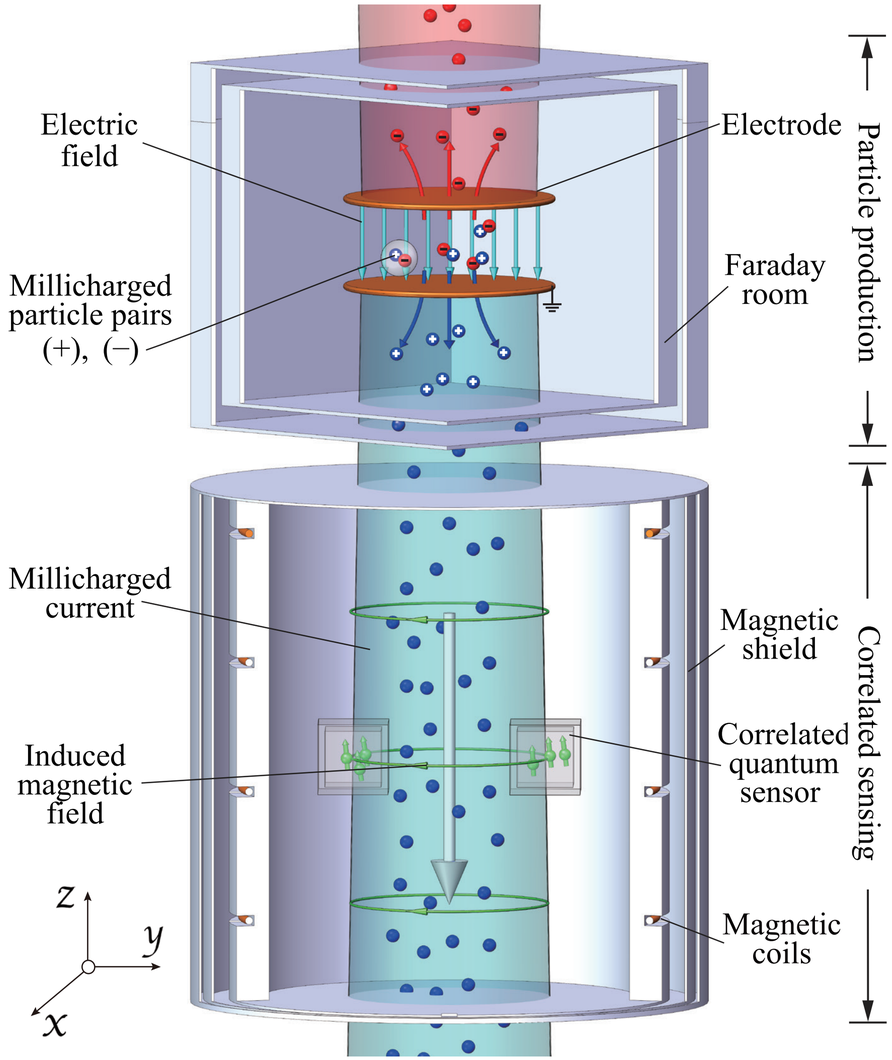
$$B_\chi \approx \frac{1}{2} j_\chi r \approx 6\,\mathrm{aT} \left(\frac{\epsilon}{10^{-7}}\right)^3 \left(\frac{E}{10\,\mathrm{kV/cm}}\right)^2 \left(\frac{d}{1\,\mathrm{cm}}\right) \left(\frac{r}{10\,\mathrm{cm}}\right)$$

Our Experimental Search for MCP



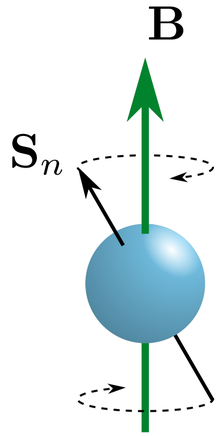
Detection: correlated quantum sensors

Our Experimental Search for MCP



Detection: correlated quantum sensors

- Atom magnetometer



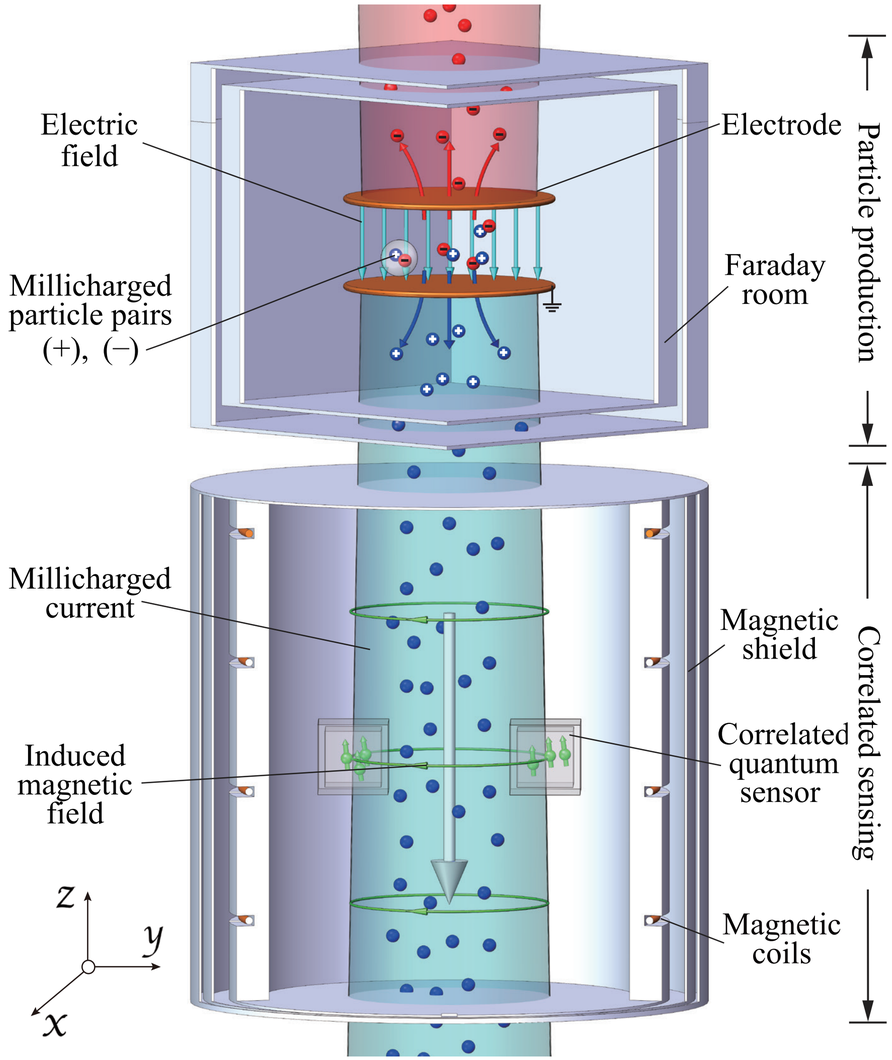
Larmor Precession

$$\tau = \gamma_N \mathbf{S}_n \times \mathbf{B}$$

Larmor Frequency

$$\omega = |\gamma_N B|$$

Our Experimental Search for MCP



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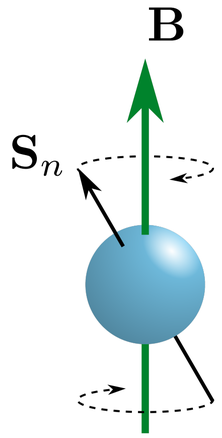


Larmor Precession

$$\tau = \gamma_N \mathbf{S}_n \times \mathbf{B}$$

Larmor Frequency

$$\omega = |\gamma_N B|$$

- Spatial correlation

  Reduce non-correlated noise

- Apply oscillating E (10 Hz)

  Avoid large magnetic noise at low frequencies

- Magnetic field sensitivity

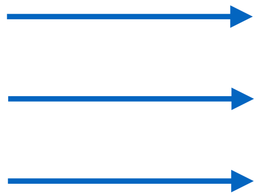
  28 aT for 17 days exposure

Finite Volume and Time Domain Corrections

- Finite volume corrections to Schwinger production rate

Dirac equation in an electric field

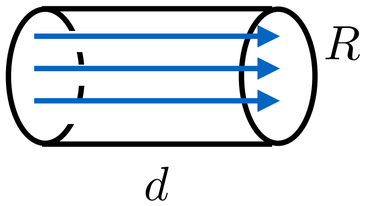
Standard Schwinger result



E field with infinite range

valid for any mass

Our experiment



Confined in a cylinder

$$q_\chi E d > 2m_\chi$$

Our experimental parameters $\sqrt{q_\chi E}d \sim 5 \quad \sqrt{q_\chi E}R \sim 100$

Finite volume correction $\eta_V \approx 0.73$

Finite Volume and Time Domain Corrections

- Finite volume corrections to Schwinger production rate

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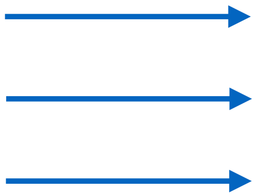

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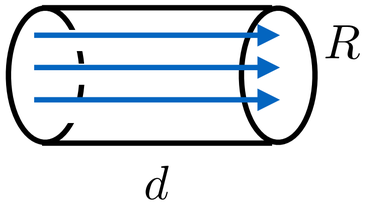

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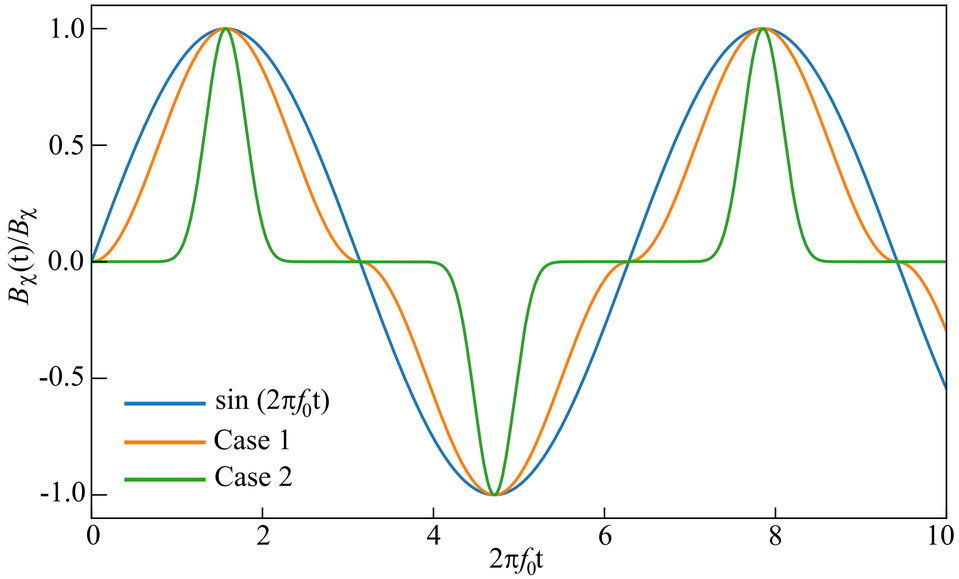
- Corrections in the time domain

Our signal is not sinusoidal



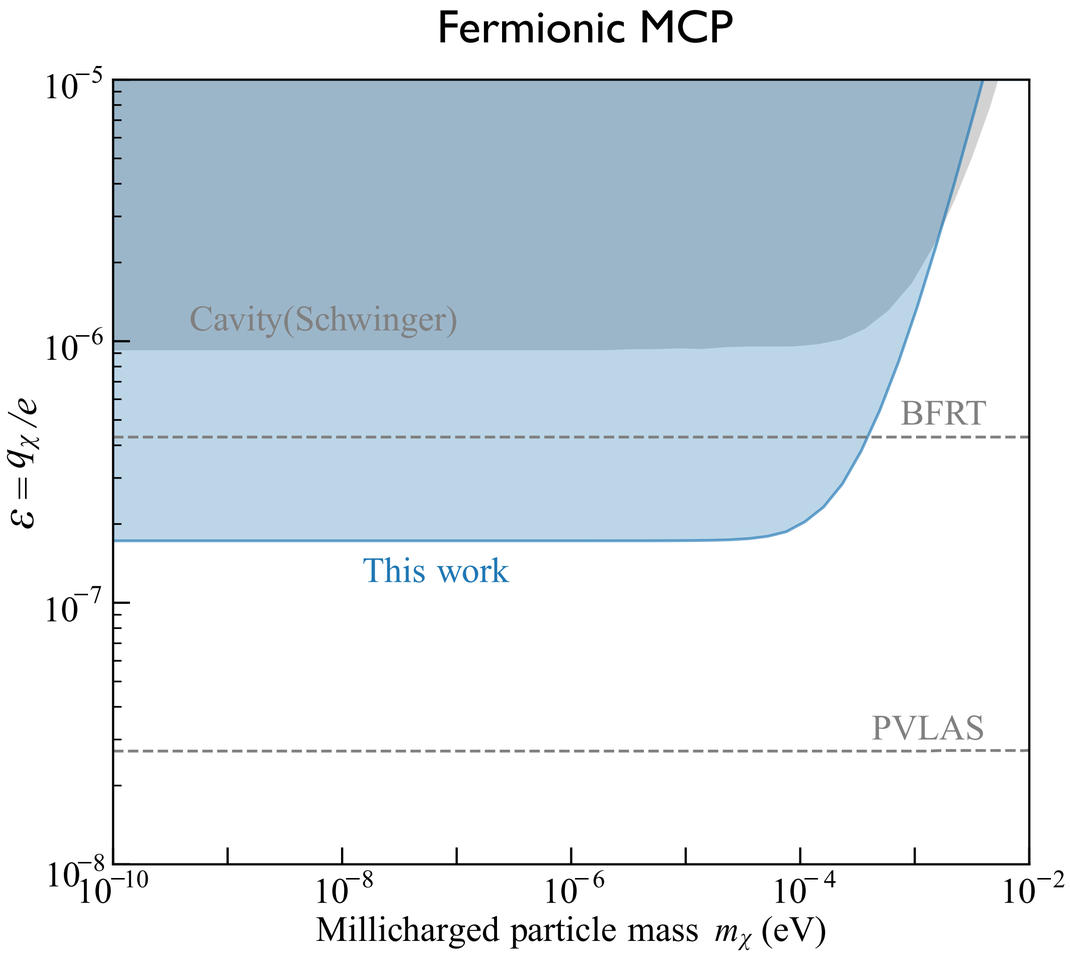
$\epsilon = 1.7 \times 10^{-7}$, $m_\chi = 10^{-8}\text{eV}$ Case 1

$\epsilon = 1 \times 10^{-5}$, $m_\chi = 5 \times 10^{-3}\text{eV}$ Case 2

Time domain correction $\eta_t \approx 0.85$ Case 1

Constraints on MCP

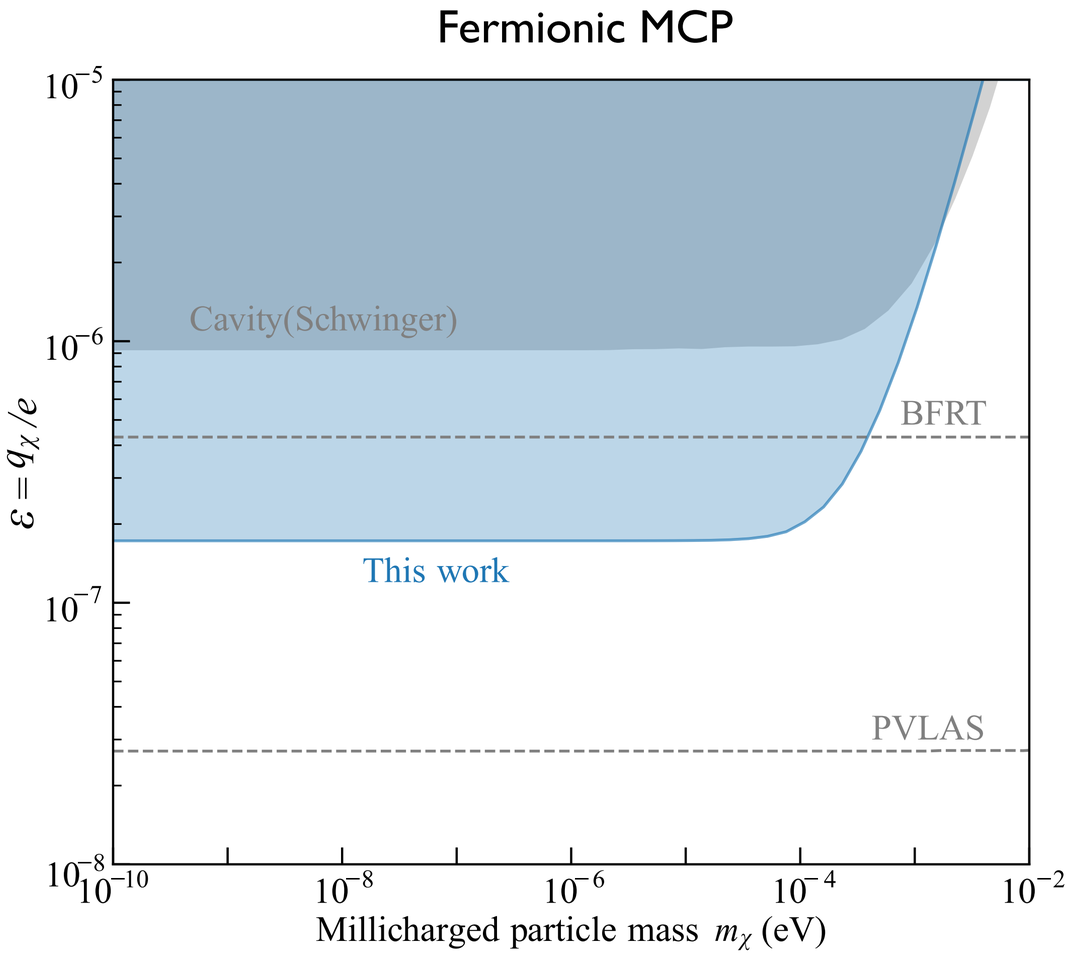
Constraints on MCP



Model independent constraint:

$$\epsilon \leq 1.5 \times 10^{-7} (\eta_V \eta_t)^{-1/3} \left(\frac{\delta B}{20\,\mathrm{aT}} \right)^{1/3} \left(\frac{E}{10\,\mathrm{kV/cm}} \right)^{-2/3} \left(\frac{r}{10\,\mathrm{cm}} \right)^{-1/3} \left(\frac{d}{1\,\mathrm{cm}} \right)^{-1/3}$$

Constraints on MCP



- Cavity: energy loss from Schwinger production of MCP

Gies, Jaeckel, Ringwald, *EPL*, 2006

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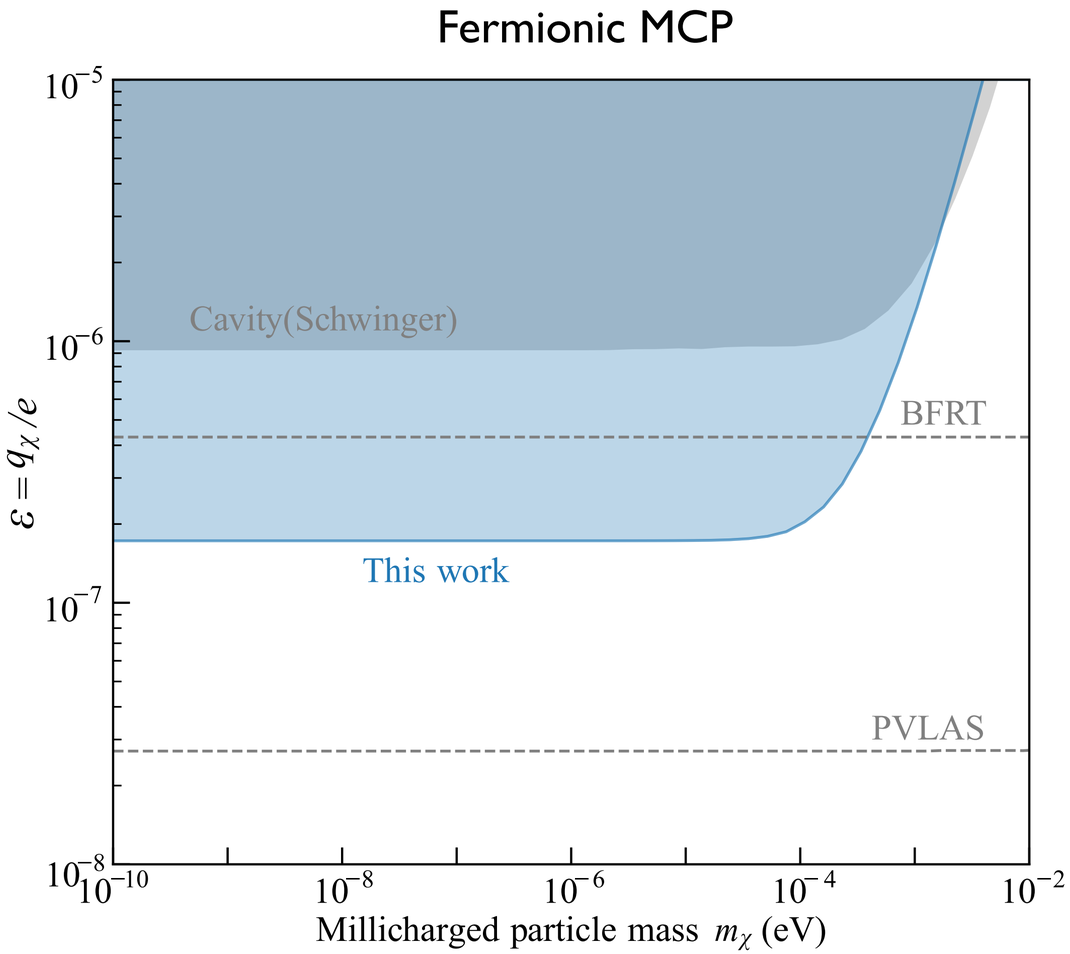
Constraints on MCP



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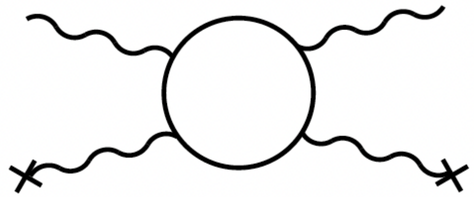
- BFRT/PVLAS: vacuum magnetic birefringence and dichroism



vacuum magnetic birefringence

Ejlli et.al, *Physics Reports*, 2020

can be relaxed due to cancellation between scalar and fermion MCPs

Ahlers, Gies, Jaeckel, Ringwald, *PRD*, 2007

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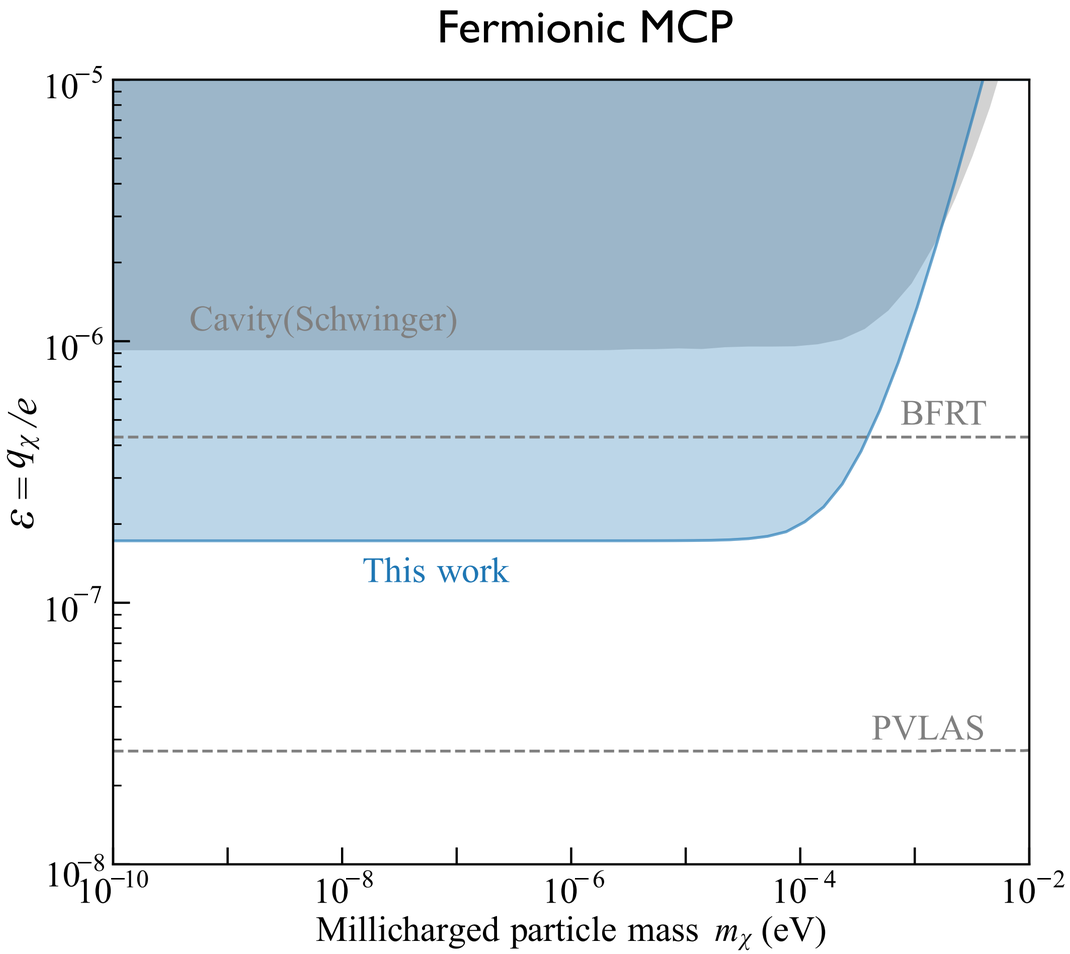
Constraints on MCP



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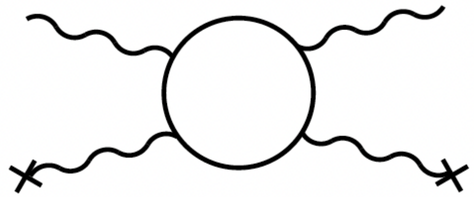

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- Additional strong constraints for bosons due to bose enhancement

  Berlin, Harnik, Li, Xu, 2024

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$$\epsilon \leq 1.5 \times 10^{-7} (\eta_V \eta_t)^{-1/3} \left(\frac{\delta B}{20\,\mathrm{aT}}\right)^{1/3} \left(\frac{E}{10\,\mathrm{kV/cm}}\right)^{-2/3} \left(\frac{r}{10\,\mathrm{cm}}\right)^{-1/3} \left(\frac{d}{1\,\mathrm{cm}}\right)^{-1/3}$$

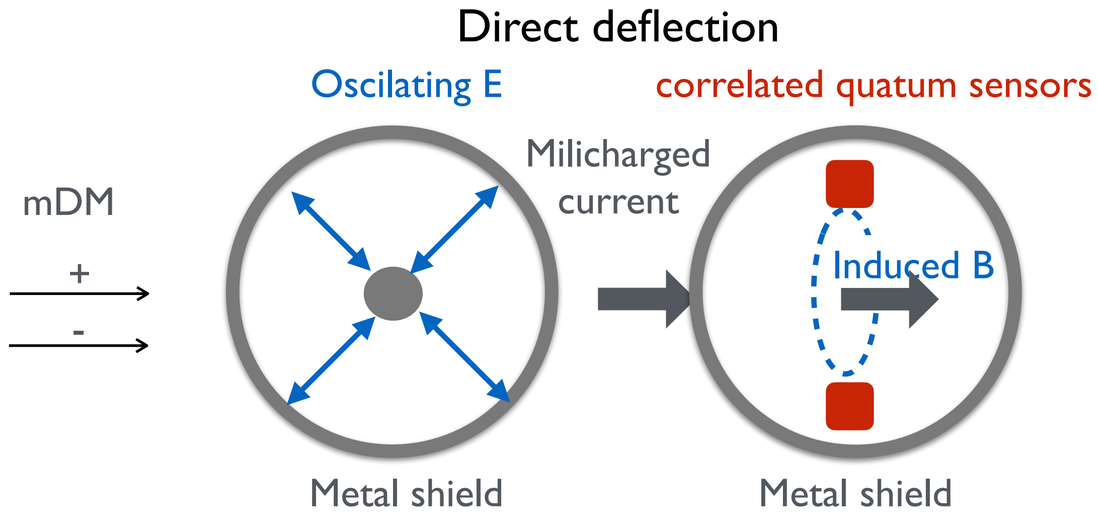
Future Directions

- Sensitivity improvement

  Higher E field: operating in vacuum

  Higher Q: pickup coil with resonant LC circuit

- Probing millicharged dark matter:

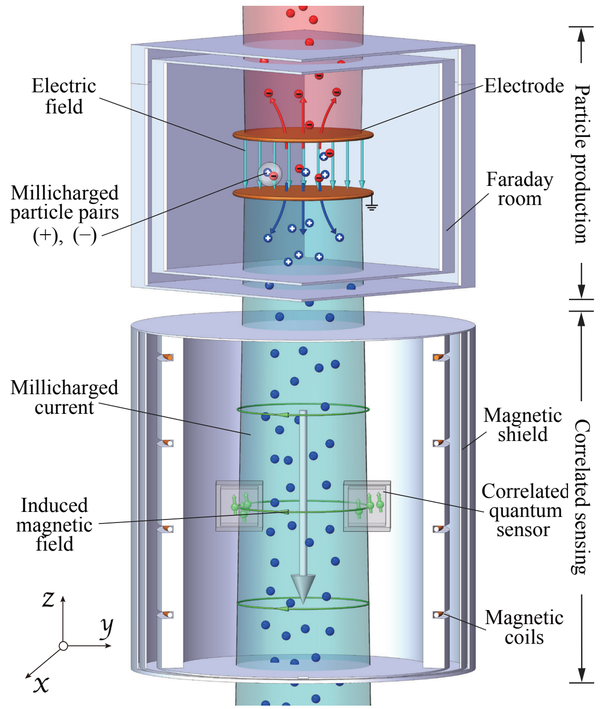


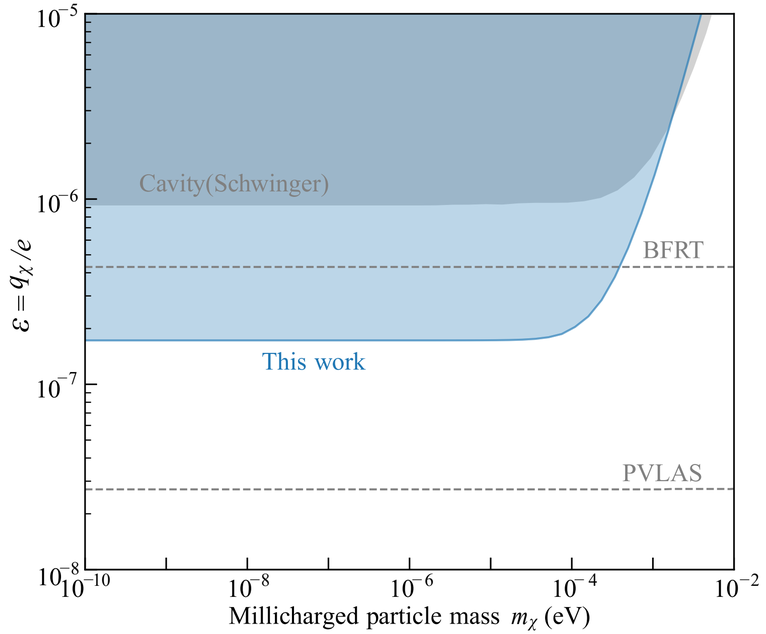
Projected constraint on millicharged DM

$$\epsilon \lesssim 10^{-8} \left(\frac{m_\chi}{\mathrm{keV}}\right)$$

Conclusions

- Low mass millicharged particles/dark matter are challenging to detect in laboratory
- MCP generated from Schwinger production form millicharged current can induce magnetic fields
- We use correlated quantum sensors to place new constraint $\epsilon \lesssim 10^{-7}$ for low masses
- This platform can probe millicharged DM via direct deflection





Thank you!